Preliminary Residual Stress Mapping of GRCop-84 Fabricated by SLM

Robert Minneci
The University of Tennessee

Claudia Rawn (UTK), Jeff Bunn (ORNL), Jared Floyd (UTK), Zachary Jones (NASA)

Material Overview: GRCop-84

Glenn **R**esearch **Cop**per Alloy

NASA Glenn Research Center

- Starting At%: Cu-8 Cr-4 Nb
- Copper Matrix:

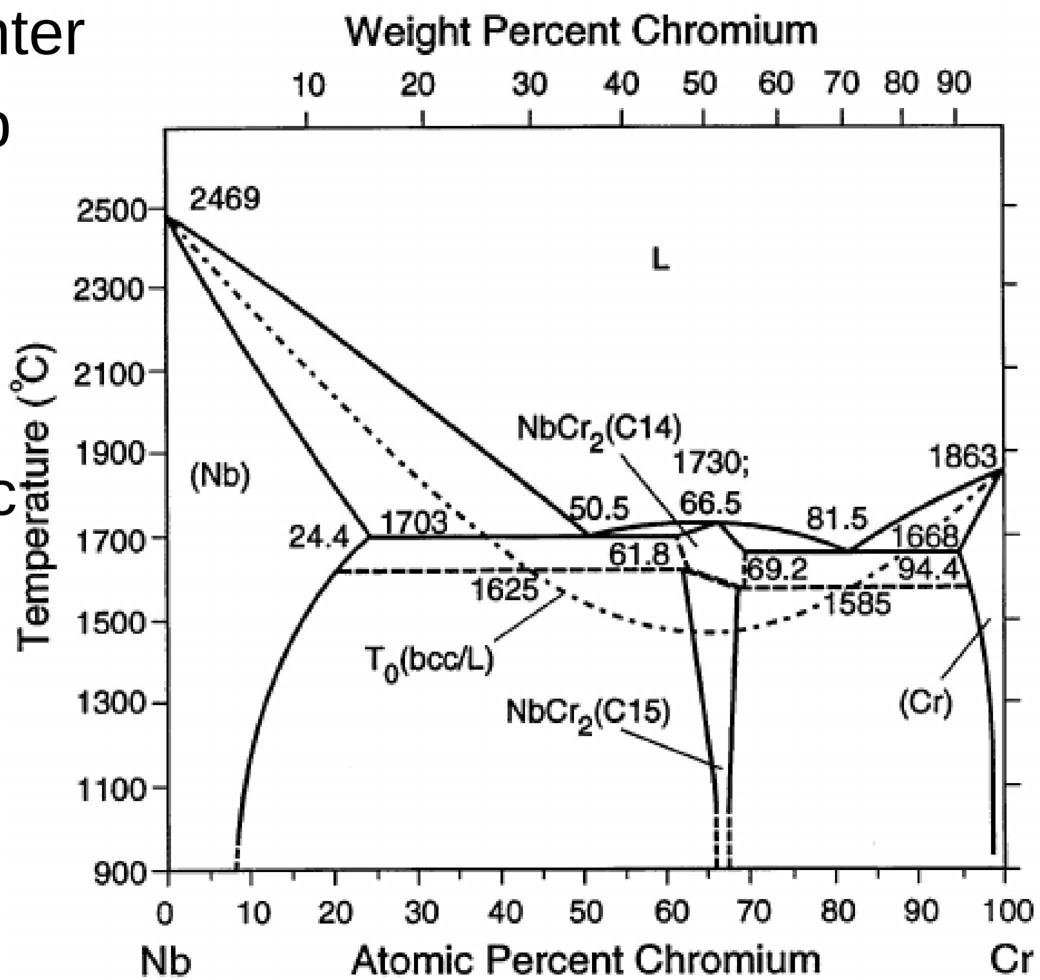
  fine intermetallic

  dispersion Cr_2Nb

  Laves phase C15 - cubic

Developed for reusable launch vehicles

- Competing with other copper precipitate-strengthened alloys
  - NARloy-Z, AMZIRC, Oxygen Free Cu (OFHC Cu)



Phase diagram from: Thoma et. al. *Elastic and Mechancial Properties of Nb(Cr,V)2 C15 Laves phases*

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SpaceX makes aerospace history with successful launch and landing of a used rocket

by Loren Grush | @lorengrush | Mar 30, 2017, 7:07pm EDT

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After more than two years of landing its rockets after launch, SpaceX finally sent one of its used Falcon 9s back into space. The rocket took off from Cape Canaveral, Florida, this evening, sending a communications satellite into orbit, and then landed on one of SpaceX's drone ships floating in the Atlantic Ocean. It was round two for this particular rocket, which

https://www.theverge.com/2017/3/30/15117096/spacex-launch-reusable-rocket-success-falcon-9-landing

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Application Related Properties

High Heat Flux Applications ≤ 700 °C

Excellent high temperature properties

- Low thermal expansion
  - 7% less than pure Cu at hot wall (400-600°C)
  - Significantly higher lifetime
- High thermal conductivity
  - 305-320 W/m*K (75-84% of pure Cu)
- High electrical conductivity
- Tensile strength
  - Excellent retention at high temp.
- High creep resistance
- Long low-cycle fatigue lifetime
- Enhanced oxidation resistance

Hot-fire test of GRCop-84 Liner, image from: Loewenthal, William & Ellis, David. *Fabrication of GRCop-84 Rocket Thrust Chambers.* Slide 16

Microstructure

- Cr_2Nb has minimal solid solubility with copper
  - Minimizes coarsening, grain size remains consistent
    - 1-5 µm copper matrix grains
  - Extremely stable up to 800°C
- Cr_2Nb particles pin copper grain boundaries
  - **Hall-Petch** mechanism
    - Dependence of strength on grain size (2/3)
  - **Orowan** strengthening
    - Dislocation bow from particles (1/3)
- Forms layer of Cr-Nb oxides below copper oxide layer
  - Slight excess of Cr to prevent Nb-H embrittlement

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Additive vs Traditional

AM outperforms traditional

- **Geometry**
  - Thinner wall capabilities
    - Better thermo-mechanical properties
  - Built-in cooling channels
    - Increased temperature margins
- **Fabrication time**
  - 3-9 months to 1 month lead
    - Compared to HIPed and wrought
  - Can be built in-house (MSFC)
- **Properties (after HIP)**
  - Porosity reduction
    - Greater or equal to traditional
    - Fully dense (greater than 99.9%)

Image credit: NASA/MSFC/Emmet Given *Nasa 3-D Prints First Full Scale Copper Rocket Engine Part*

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Neutrons and GRCop-84

- Few existing neutron studies
  - Effectively none for AM GRCop-84
  - Why?
    - AM development
- Still under development
  - Needs supporting data
  - Direct benefit of results
  - Carries general AM concerns
- Proposal Goals
  - Initial simplicity for familiarization
    - Begin with bulk residual stress/strain
    - Thermal misfit
  - Conduct multiple studies building up to comprehensive study
  - Potential modeling

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Residual Stress

- High thermal gradients
  - 10^4 to 10^6 K/s cooling
  - Excess RS can lead to plastic deformation
    - Before heat treatment can be performed
    - Build has to be restarted, significant loss

Image credit: NASA/MSFC/Emmet Given *Nasa 3-D Prints First Full Scale Copper Rocket Engine Part*

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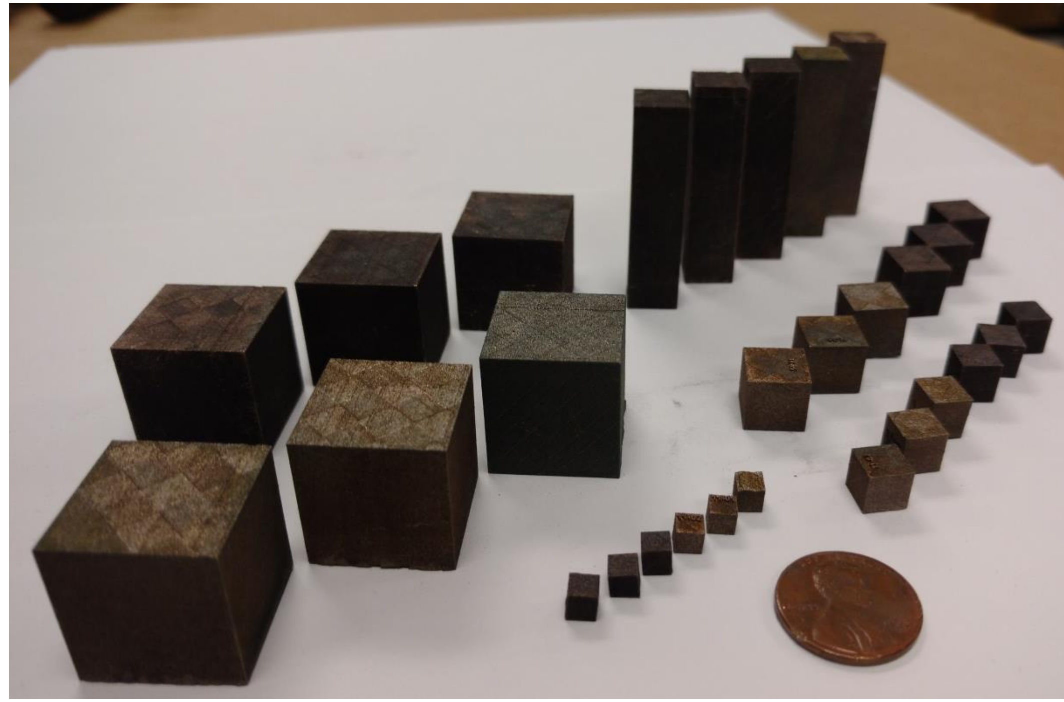
Samples - MSFC

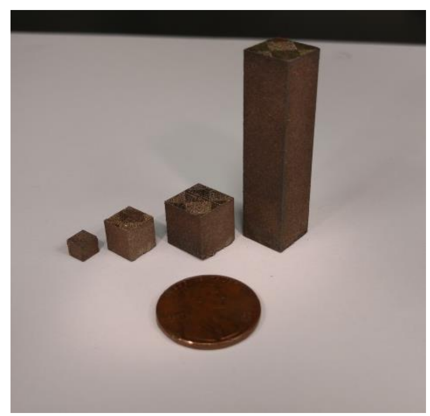


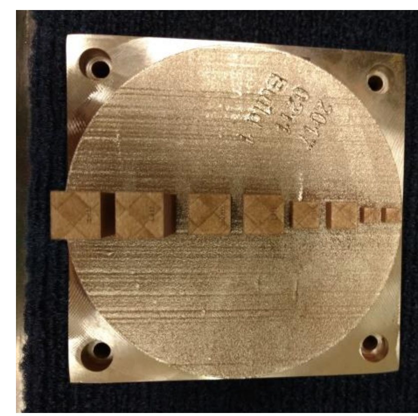
Built on Concept Laser M2

- SLM – Chess Pattern
- Powder bed fusion
- Pre- and post-HIP
- Removed from build plate by EBM

Simple geometries

- 20,10, 7, and 4 mm cubes
- 10x10x40 pillars



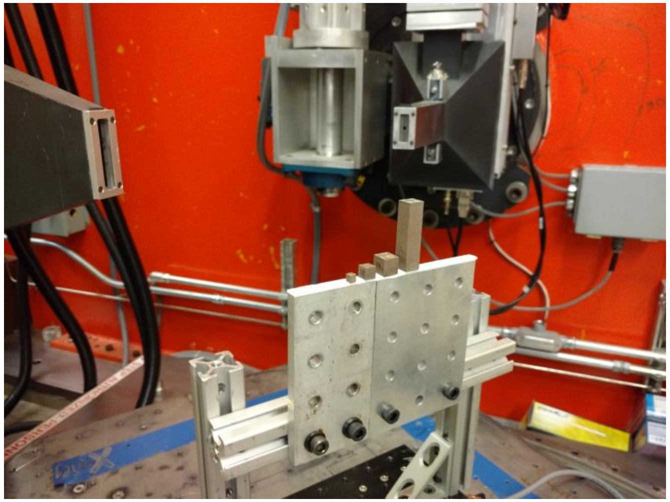


Concept Laser Image Credit:http://3dprintingdatabase.org/en/services/m2-cusing

GRCop-84 Beamline Setup

Experiment conducted at HFIR

- NRSF2 HB2B
  - Neutron Residual Stress Mapping Facility
- May 2017



Scanning Parameters

- 2 mm^3 gauge volume
  - <5 minutes per point
    - 40 minutes for 1 mm^3 gauge vol.
- 422 monochromator ~1.54 Å
  - Cu 311 reflection ~90° 2θ

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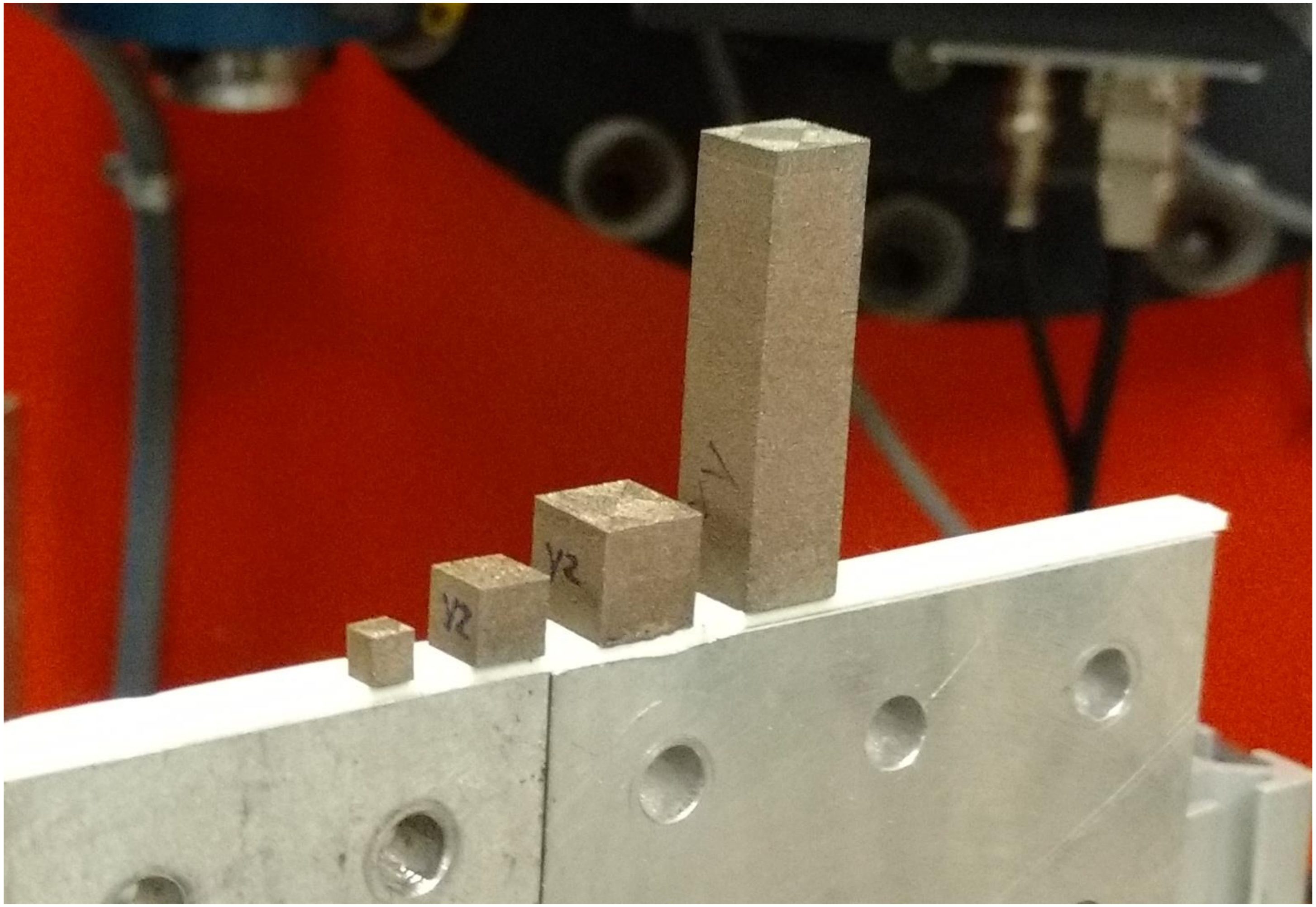
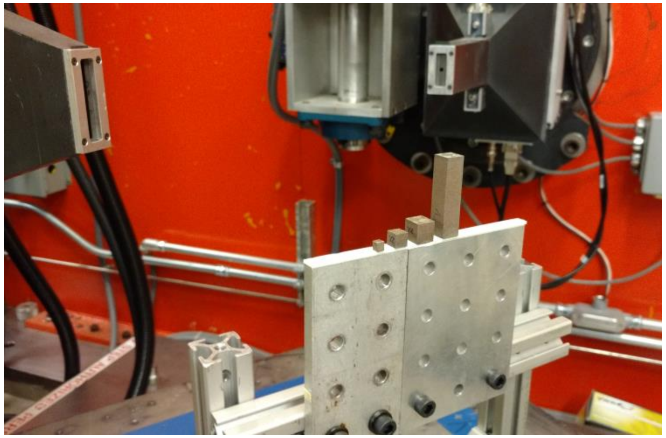
Samples Measured



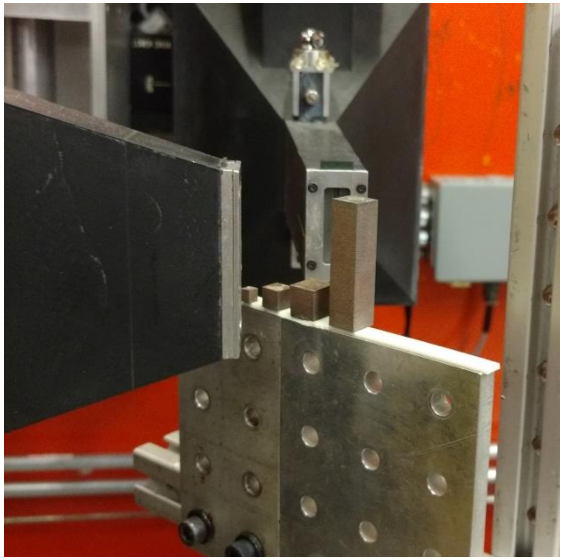
- 4, 7, and 10 mm cube
- 10 x10 x 40 mm pillar

Sample Orientations/Mounting

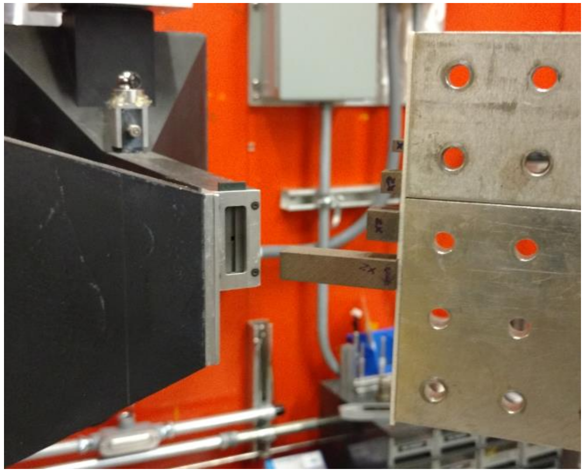
X-Direction



Y-Direction



Z-Direction



Strain Calculation

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{hkl}^{o}}{d_{hkl}^{o}}$$

Stress Calculation

$$\sigma_{ij} = \frac{E}{1+v}\left(\varepsilon_{ij} + \frac{v}{1-2v}\left(\varepsilon_{11}^{hkl} + \varepsilon_{22}^{hkl} + \varepsilon_{33}^{hkl}\right)\right)$$

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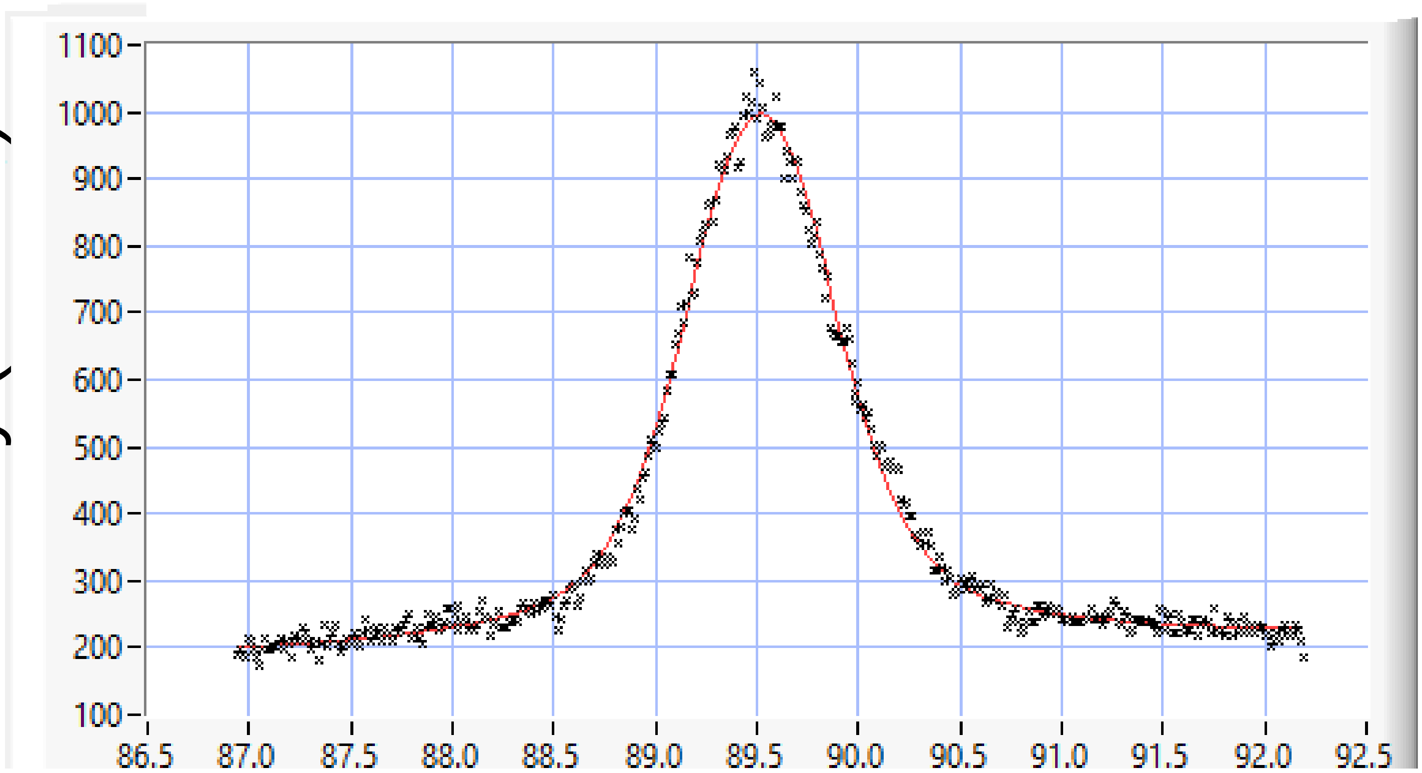
Residual Strain Measurement

Intensity (counts)



Angle 2θ°

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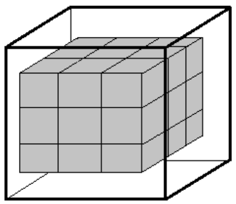
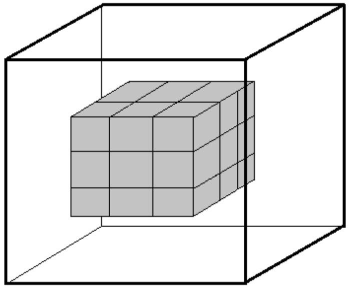
Beamline Experiment

1. Volumetric Study

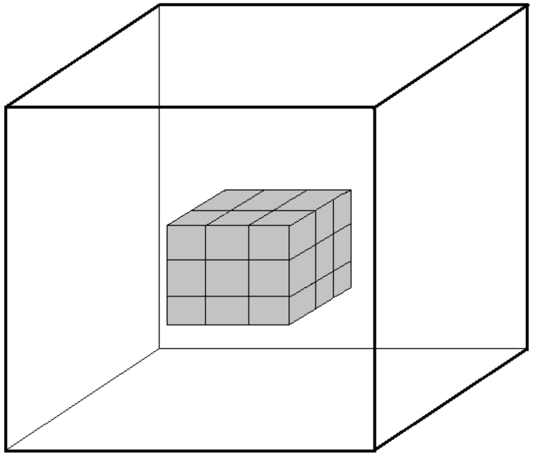


4 mm

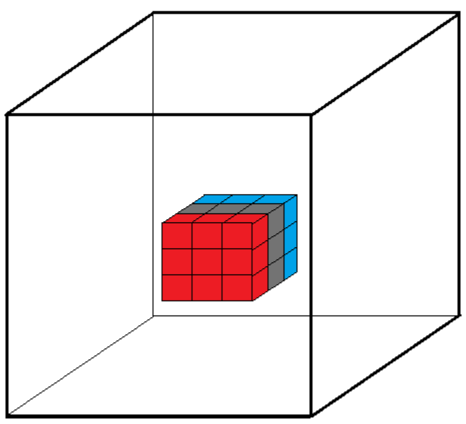
(only compact)



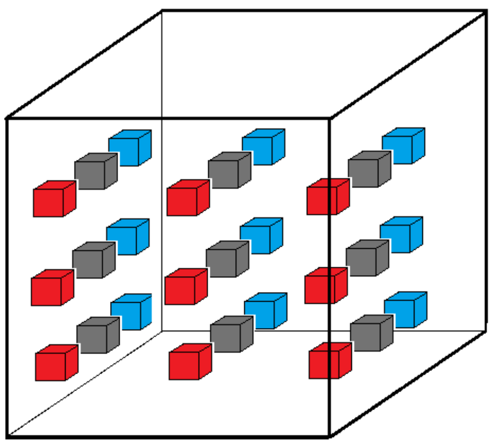
7 mm



10 mm

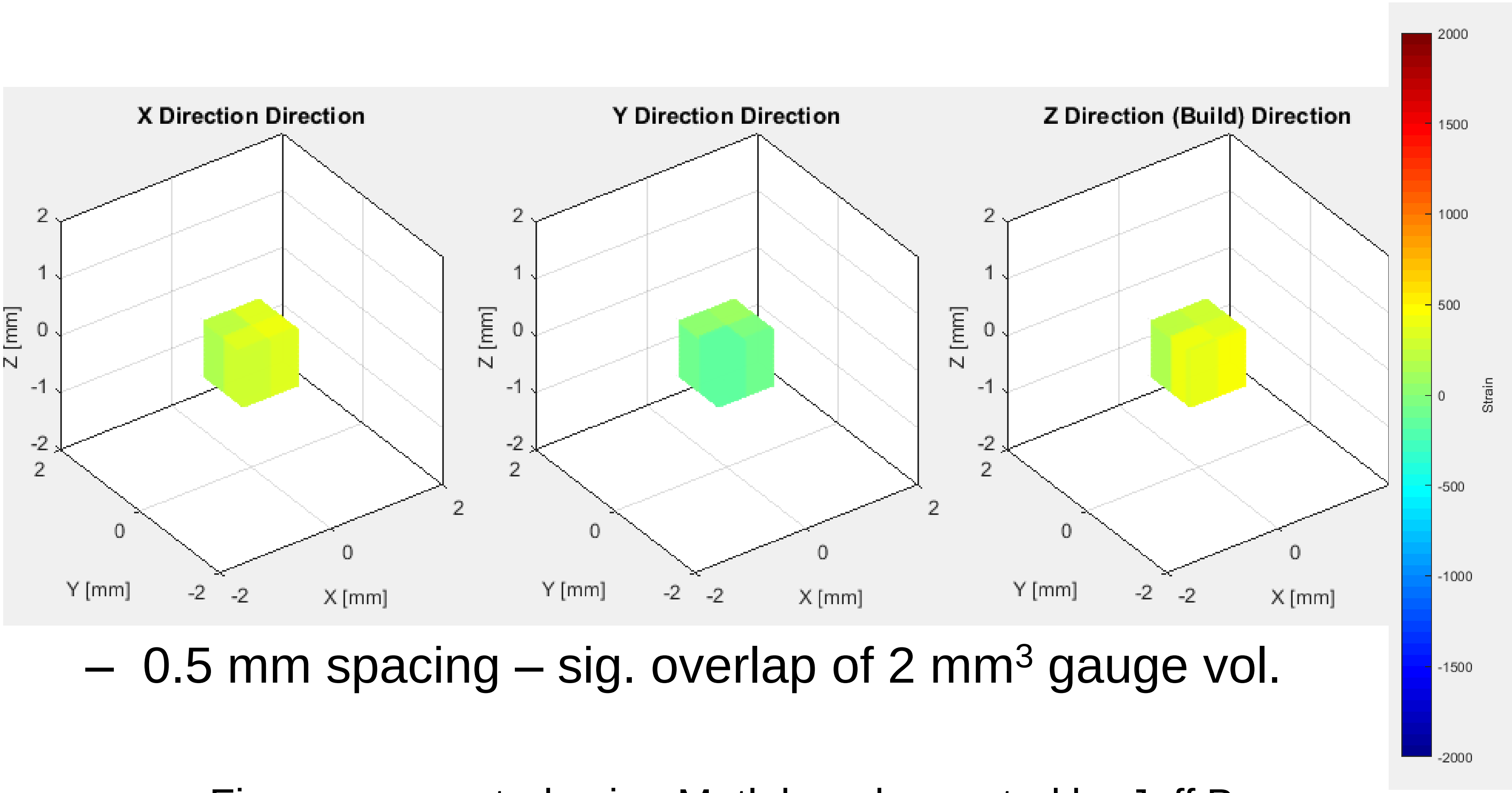


Compact



Spread

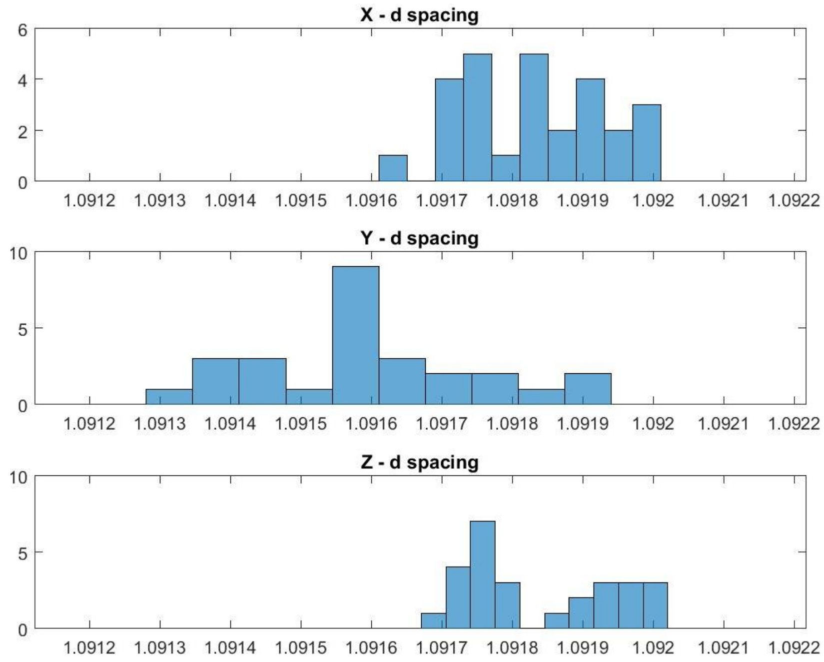
Volumetric Results
4 mm cube strain



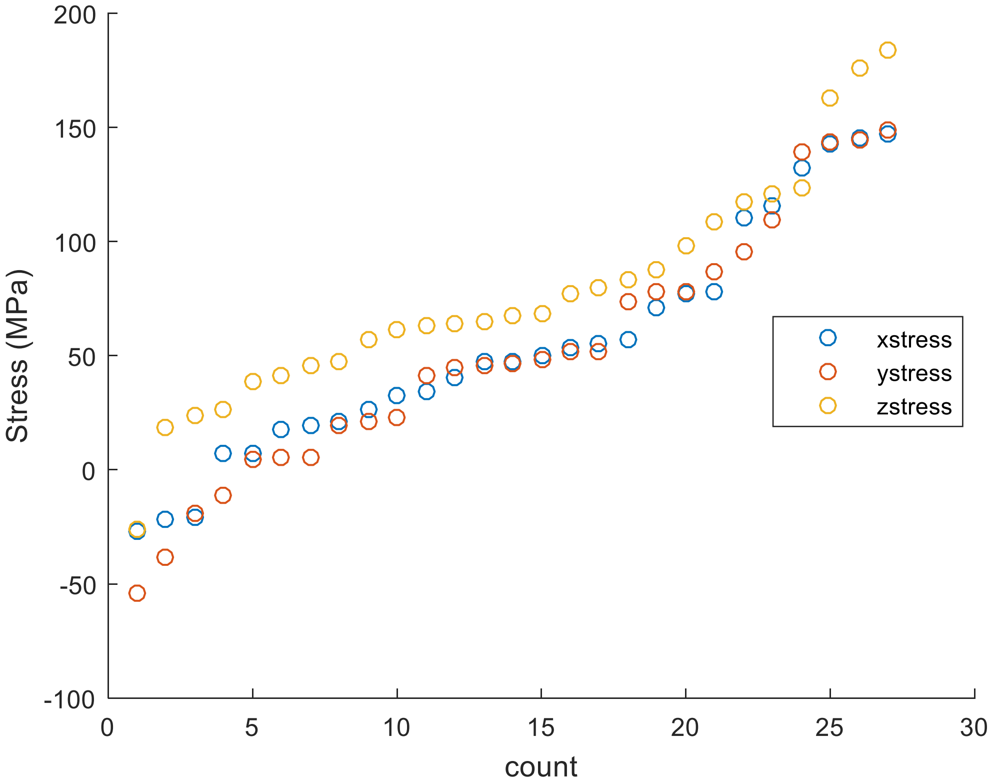
– 0.5 mm spacing – sig. overlap of 2 mm^3 gauge vol.

- Figures generated using Matlab code created by Jeff Bunn

Volumetric Results
Example Statistics



4 mm Cube d spacing distribution



10 mm Cube stress distribution

Estimated d_o – 1.091517 Å

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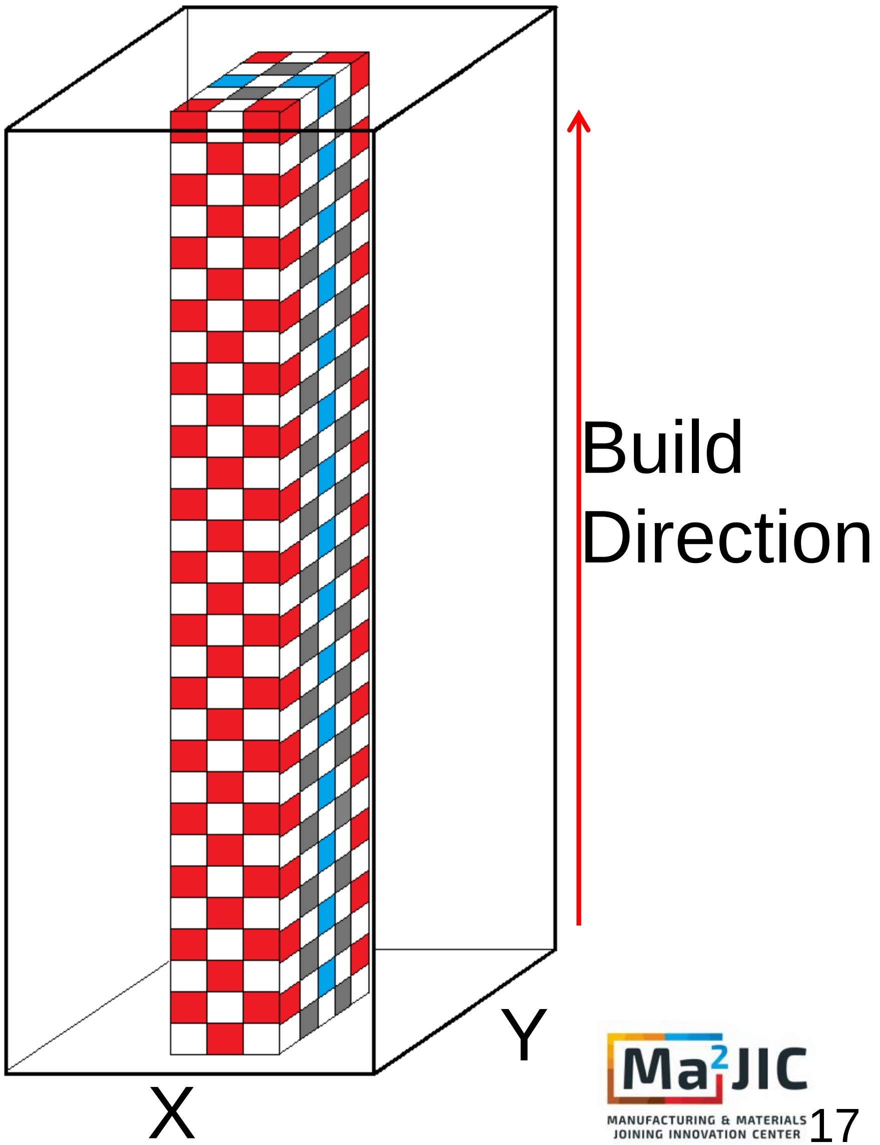
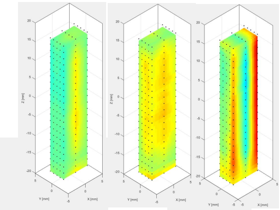
Pillar Experiment

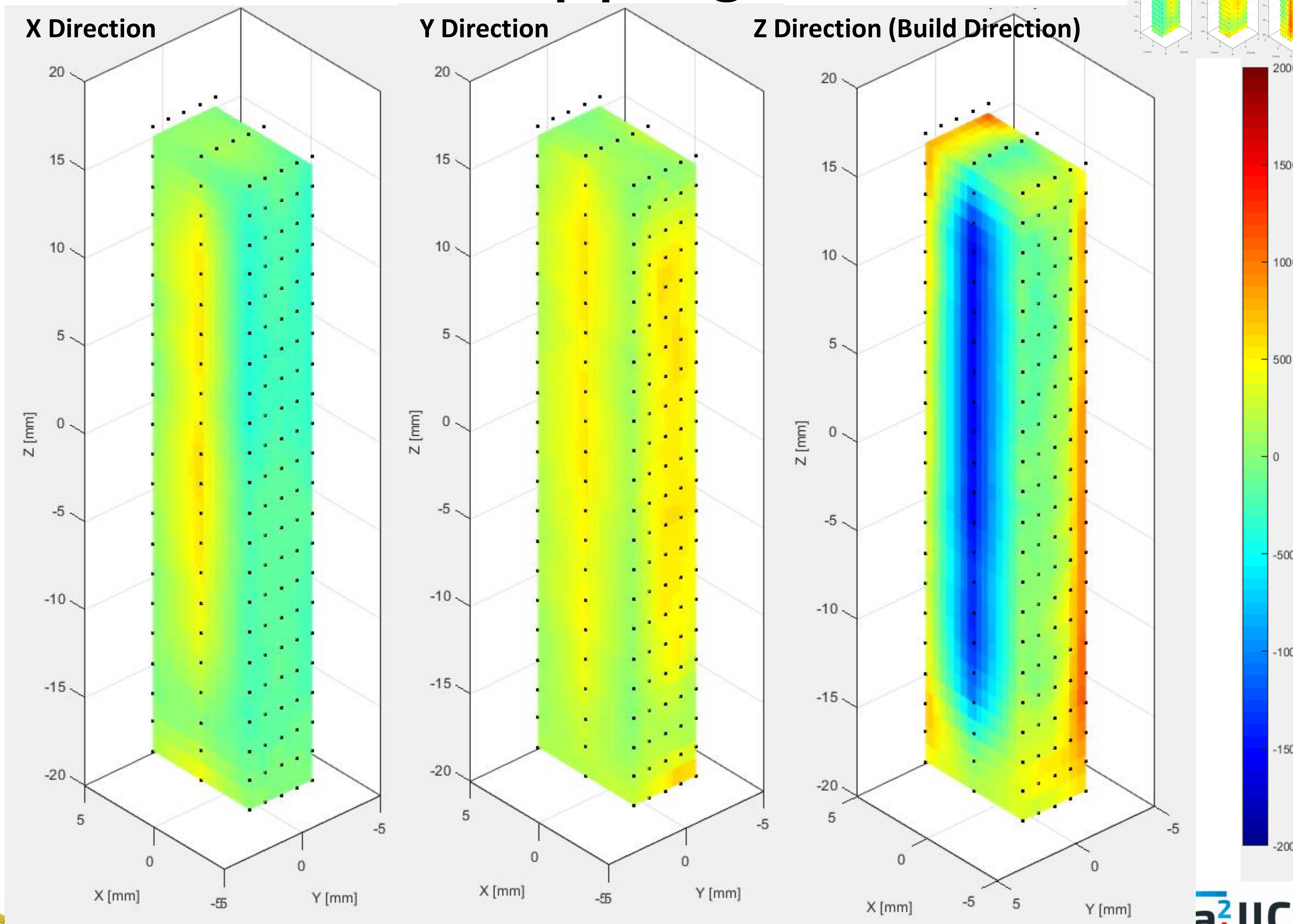
2. Pillar Study
   - 3x5x22 data points
   - Sample goal
     - Function of distance from build-plate

ADD X Y Z Labels



Pillar Mapping Strain





Strain range: 0.00204 to -0.0018

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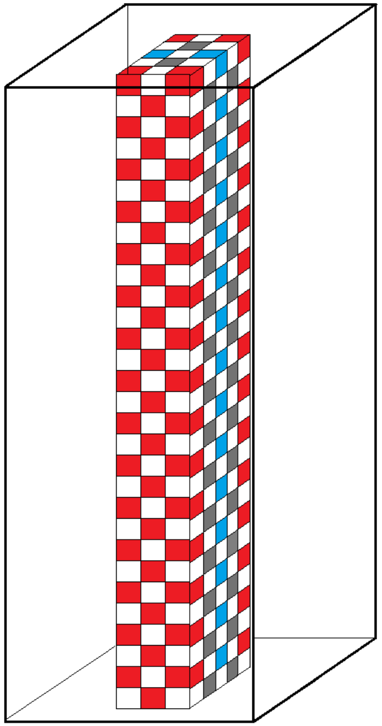
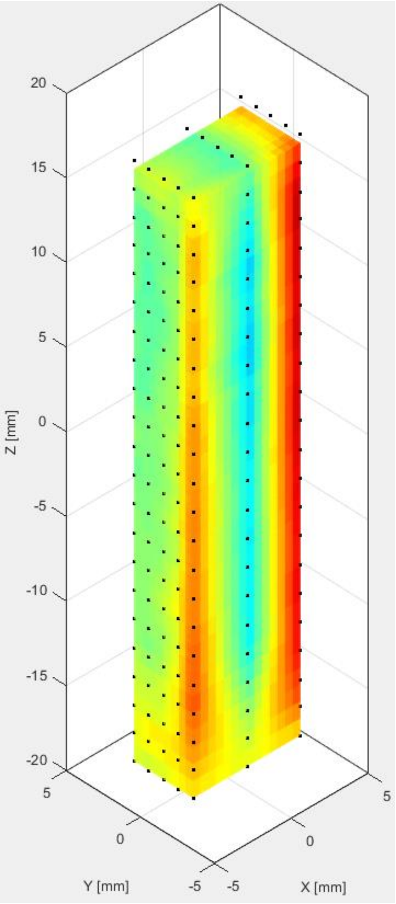
Pillar Results

- Lit. Elastic Modulus 86 – 111 GPA
  - Being determined by RUSS
    - Resonant UltraSonic Spectroscopy
  - Residual stress could be closer than expected to yield stress
- d_o may change
- Replicate pillar scan
  - with HIPed sample





Conclusions

GRCop-84

- Excellent high temp. properties
  - High heat flux applications
- One of the few cases where AM is better than traditional
  - Complex geometry capabilities
  - Lower fabrication time
  - Equal or greater properties
- Relatively easy to print
  - Assumed low RS concentrations

Neutron Study

- Collected lots of data
  - Stress relieved at interface with build plate
    - Data near bottom needs to account for this
  - 4, 7, and 10 mm cubes
    - Cube samples' better for statistics than mapping
  - 10x10x40 mm pillar
    - HIPed samples to be run
  - +0.00204 to -0.0018 strain
    - Depending on E may be close to yield stress

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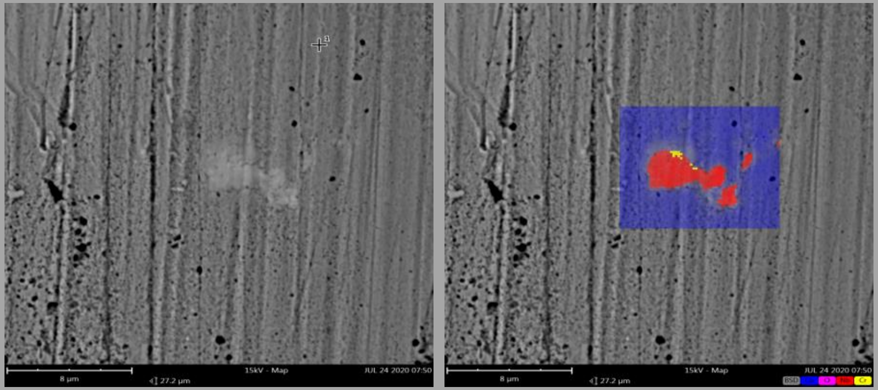
Future Work

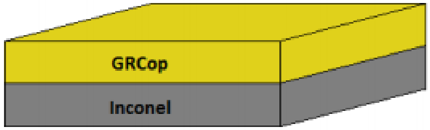
Next Proposal

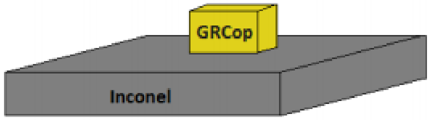
- Accepted
  - Sometime later this year
- Thermal and Shape Misfit Analysis
  - GRCop-84 and IN718/625
    - Alloy composite by direct SLM
    - HIPed and unHIPed
  - Finite and semi-infinite cases
  - Difficult d_o calculation

Future Objectives

- Complete data analysis
- Characterization
  - SEM
  - EDS
  - Surface XRD
    - HIPed and unHIPed







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Thank you

Questions?

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